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Adaptive Optics Correction Using Coherently Illuminated Diffractive Objects

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ABSTRACT

Adaptive Optics (AO) is an established technique for improving image quality and compensating for aberrations induced by focusing through samples with varying thickness and refractive index. Future optical data storage schemes with multiple data layers may require the correction capabilities of AO systems. However, the diffractive phase introduced by light reflected from optical storage media might be problematic for high-performance systems. A laser beam focused onto grooved media has a reflection with a baseball-shaped variation in the pupil, caused by the overlap in diffracted orders with the zero-order reflection. This pupil variation is significant in intensity, and simulations and experiments show that there is an associated small variation in phase. If the diffractive phase is sufficiently small, measurement of the total phase with aberrations by a wavefront sensor could enable application of AO correction with diffractive media samples.

Simulations and experiments are presented to examine the capability of an adaptive optics microscope system to compensate for diffractive effects with a coherently illuminated sample. AO systems are commonly implemented with incoherent objects, but this could be extended to other applications by characterizing the performance of an AO system with a coherent reflection from a diffractive surface. Data storage media are used as targets for investigating these intensity and phase variations caused by coherence effects, with well-defined grating parameters creating diffraction patterns that are modeled and verified experimentally. There are potential applications outside of data storage, such as coherent free-space optical communication.

Keywords: Adaptive Optics, Diffraction, Coherent Illumination, Optical Data Storage, Diffractive Samples

1. INTRODUCTION

1.1 Adaptive Optics

Adaptive Optics (AO) is an established technique for improving image quality and compensating for extrinsic aberrations induced by imaging through samples with varying thickness and refractive index [1]. AO systems are commonly implemented with incoherent objects, such as astronomical observations, microscopy of biological samples, or retinal imaging in ophthalmology. To extend this to coherent illumination, it is not well understood how an AO system will operate with a coherent reflection from a diffractive system. This work explores the capability of an AO system to compensate for diffractive effects with a coherently illuminated system. Results are also presented for open-loop AO correction of aberrations with a diffractive sample.

1.2 Theory

As an example of a coherently illuminated object, traditional data storage applications use a bipolar tracking error signal (TES) to correct the position of an objective lens relative to data grooves [2]. When a laser beam is focused onto the grooved storage media, the reflected +/-1 diffracted orders overlap with the zero-order reflection, forming a baseball-like TES variation, as shown in Figure 1 [2,3]. Reflection from a coherently illuminated phase grating produces a significant variation in intensity in the pupil, but only a small variation in phase. It is crucial for adaptive optics to have precise knowledge of the extrinsic phase in order to send feedback to a wavefront compensator. AO systems would therefore be ineffective if phase gratings such as the data storage device depicted in Figure 1 introduced additional significant phase variations due to diffraction. Simulations and experiments described in the following sections suggest that it is possible to use AO with diffractive samples, due to the relatively small additional diffractive phase.

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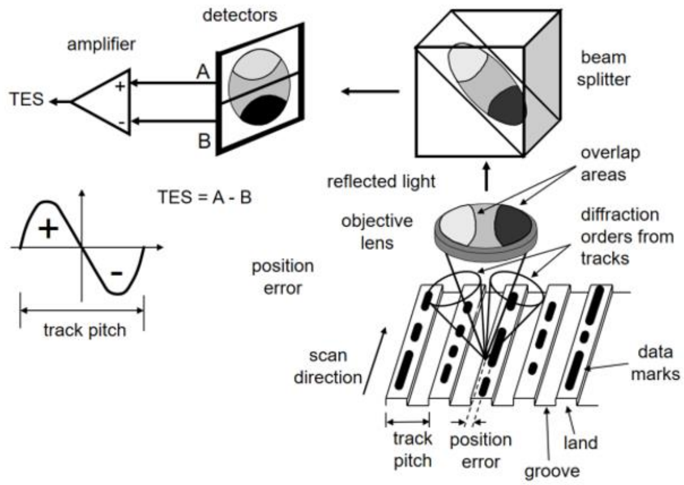


Figure 1. A focused laser beam reflected off a grooved sample creates a tracking error signal (TES) from the overlap of the first-order reflection and +/-1 diffracted orders [2].

1.3 Applications

Data storage media (CD, DVD, BD) are prime candidates as targets for investigating the effects of amplitude and phase variations caused by coherence effects in AO systems. The established industry has created disks with very well-defined grating parameters, which create diffraction patterns that can be modeled and verified experimentally. Future optical data storage schemes with multiple data layers may require the correction capabilities of AO systems. An additional application outside of data storage is coherent free-space optical communication like that reported by J. Cao et al [3].

2. SIMULATIONS

2.1 Setup

To simulate AO correction with a diffractive surface, the system in Figure 2 is modeled in MATLAB. Adding aberration to the illuminating and reflected beams emulates focusing a beam through an aberrating medium and onto a diffractive surface. Three waves of spherical aberration produces irradiance and phase patterns as shown in Figure 3. Half of the phase information is then compensated by the deformable mirror, such that in double-pass the aberration is corrected, shown in Figure 3c.

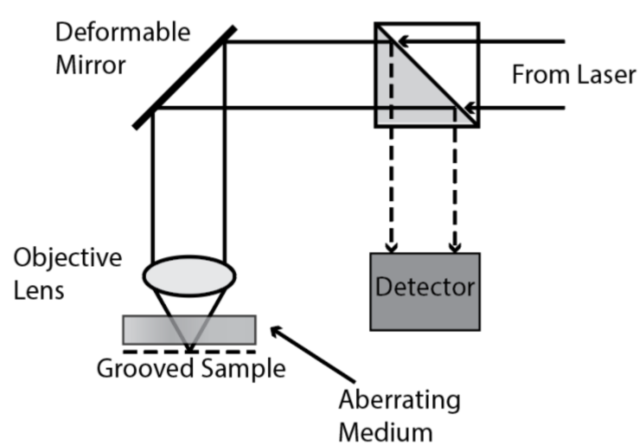


Figure 2. Diagram of the setup modeled in MATLAB.

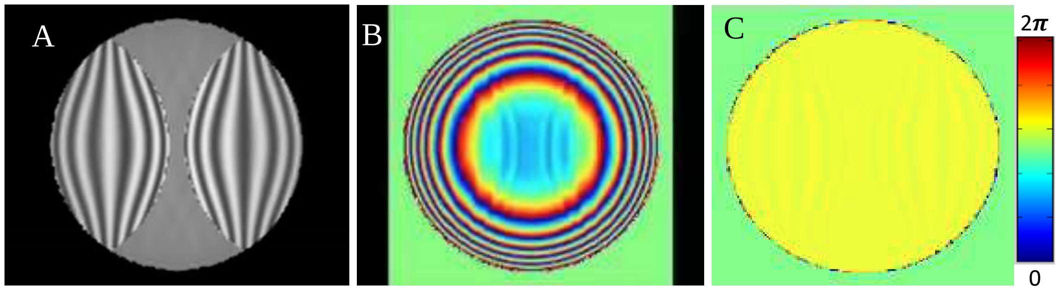


Figure 3. A) Irradiance pattern simulated for an aberrating medium with 3 waves of spherical aberration. B) Simulated phase for 3 waves for spherical aberration. The overlap pattern is visible but dominated by the induced spherical aberration. C) Simulated phase after compensating for the aberration with the deformable mirror correction.

2.2 Overlap

A wavefront sensor in an AO system with a diffractive object will detect the amplitude and phase baseball-like patterns as discussed in the previous sections. To further understand these diffractive effects, the Fourier Series coefficients c_m are calculated to predict the pupil images directly from the grating parameters. The c_m values for the zero, +1, and -1 diffracted orders take the form of equation (1) for a reflective phase grating, and Figure 3 shows the overlapping orders.

$$c_m = (e^{i\varphi} - 1)e^{(-i2\pi m y_0)}\frac{w}{d} sinc\left(m\frac{w}{d}\right) + sinc(m) \tag{1}$$

The grating duty cycle is $\frac{w}{d}$, φ is the grating phase depth, and y_0 indicates the position of the illuminating beam along the grating.

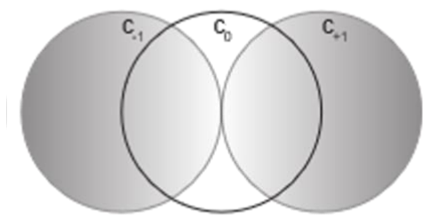


Figure 4. The Fourier Series coefficients are calculated for the zero and +/-1 orders diffracted from an object, indicating the amplitude and phase in the pupil.

2.3 Aberrations

For an imperfect system, aberrations will be also present in the overlapping regions between the 0 and +1 orders and the 0 and -1 orders. This is simulated by adding aberrations to the Equation (1), and a collection of simulated results is presented in Table 1.

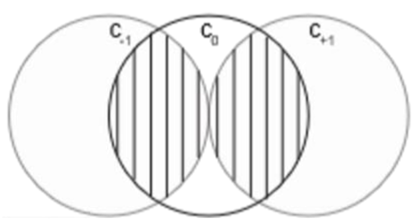
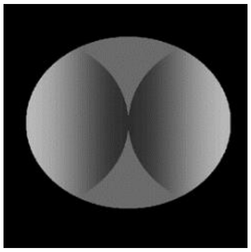
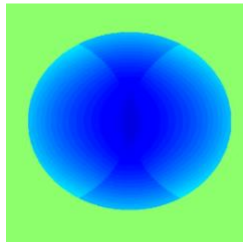
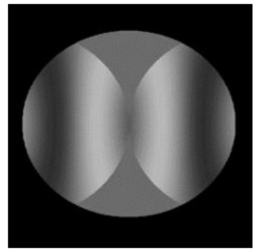
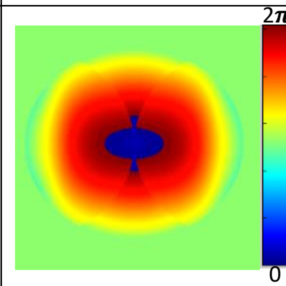
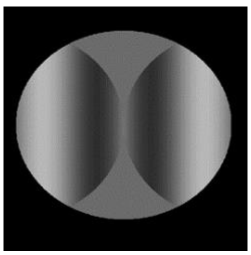
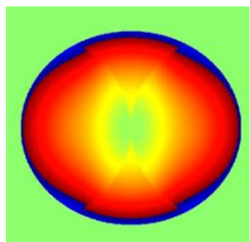
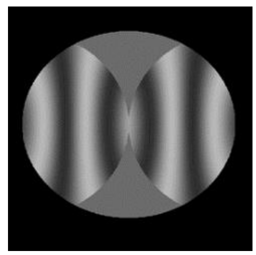
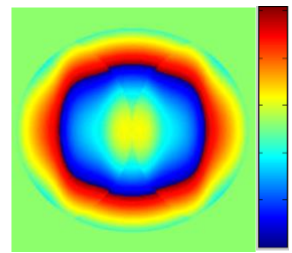
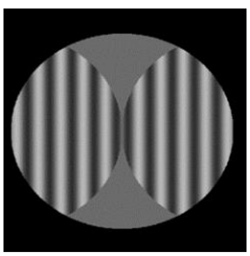
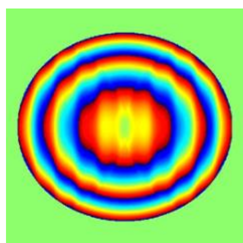
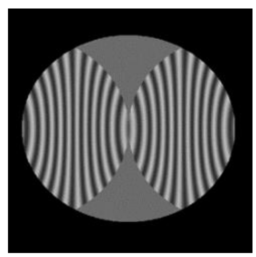
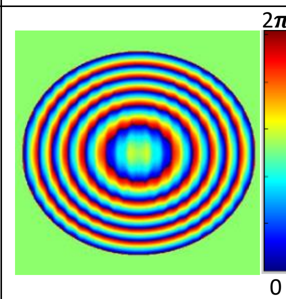


Figure 5. Modifying Equation (1) to include aberrations creates fringes in the overlapping areas of the pupil.

Table 1. Simulation Results

	Defocus		Spherical Aberration	
	Irradiance	**Phase**	**Irradiance**	**Phase**
0.5 Wave				
1 Wave				
5 Waves				

3. EXPERIMENTAL SETUP

An off-the-shelf Thorlabs AO Kit is modified to create the experimental layout, as illustrated in Figure 3. For this experiment, the wavefront sensor is a Shack-Hartmann device with 47x35 lenslets (Thorlabs WFS20-5C), and the wavefront corrector is a MEMS Deformable Mirror with a 12x12 actuator array and a 4.4mm x 4.4mm active mirror area (Thorlabs DM140A-35-UM01). A 2D scanning galvanometer mirror system (Thorlabs GVS012) enables scanning the laser illumination across the surface of the sample. The camera is an 8 Megapixel CCD detector (Thorlabs 340M-GE), and it can be optically located at a pupil or at an image plane by changing a flip lens. To utilize AO for aberration correction, the deformable mirror and wavefront sensor are positioned at optical conjugates. There must also be a conjugate position at the galvo mirrors, and these conjugates must be matched to the entrance pupil of the microscope objective. Custom LabVIEW software is developed to allow for simultaneous control of the DM, SHWFS, camera, and galvo mirrors.

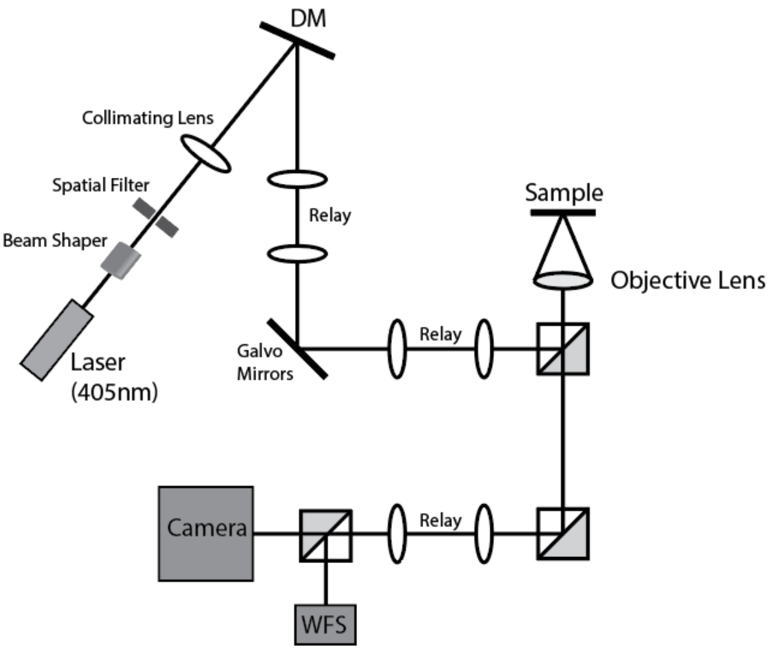


Figure 6. Experimental layout, where conjugate positions are at the deformable mirror (DM), galvo mirrors, entrance pupil of the objective lens, camera, and wavefront sensor (WFS).

4. EXPERIMENTAL RESULTS

In the following sections, two experiments are conducted to observe the patterns predicted by simulation: employing the AO components to focus through a thick optical window and observing the reflection from a data storage device. For both scenarios, focused laser illumination is scanned across the disk grooves with the galvo mirrors, the amplitude and speed of which are controlled by custom LabVIEW software. The positioning of the sample relative to the focus through the microscope objective is adjusted by a Picomotor translation stage.

4.1 Focusing through thick window

An Edmund Optics reflective grating with a period of 25microns is used as a diffractive sample. The objective lens is an achromatic doublet with 125mm focal length (Thorlabs AC254-125-A). A broadband precision window with a thickness = 12mm (Thorlabs #WG12012-A) is inserted in between the objective lens and the reflective grating, as illustrated in Figure 7. This induces both defocus and spherical aberration, visible on the camera image Figure 8b. By changing the shape of the deformable mirror, the aberrations are corrected as shown in Figure 8c.

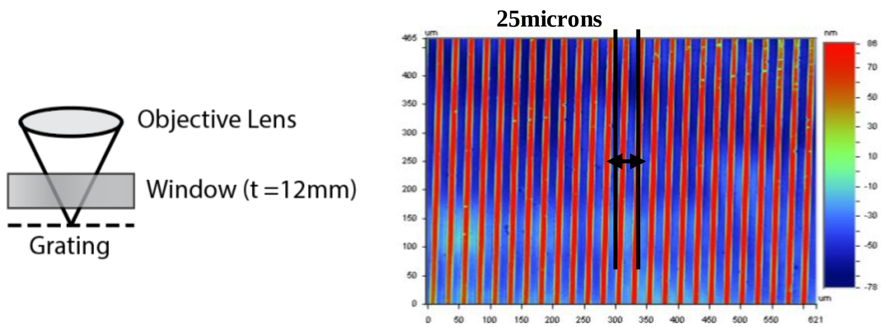


Figure 7. Left: Diagram of inserting the thick window into the experimental system. Right: Grating profile with a period of 25microns, as measured with the Veeco NT9800 Optical Profiler.

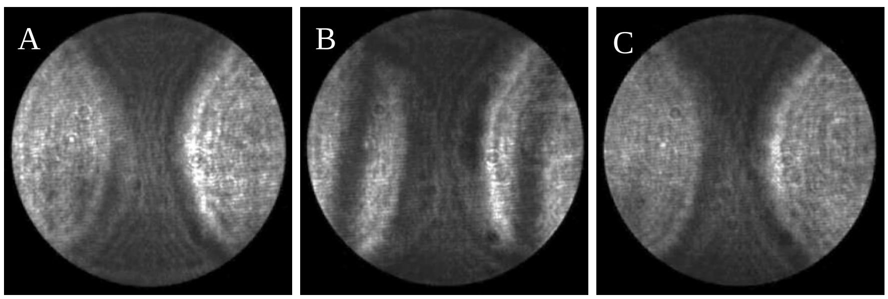


Figure 8. A) With a flat DM surface, there are no fringes in the overlapping regions of the pupil. B) Inserting a 12mm thick window into the system introduces defocus and spherical aberration and fringes are visible in the pupil. C) Changing the shape of the deformable mirror corrects for these aberrations and the pupil image returns to the ideal case.

4.2 Reflection from coated CD-R disk

The first data storage sample to be implemented in this system is a CD-R disk coated with 75nm of gold, imaged with a 10x Olympus Objective with NA = 0.25. The track pitch of 1.6microns is verified by an AFM image, as shown in Figure 9.

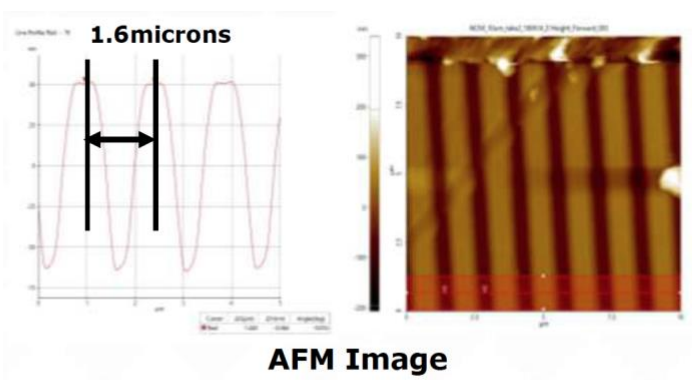


Figure 9. AFM image of gold coated CD-R sample confirms a grating period of 1.6microns.

Images of the pupil confirm the variations in irradiance as predicted by the MATLAB simulations. The patterns within each lobe of the TES baseball pattern are indicative of shearing interferometer patterns with spherical aberration and defocus as described by Malacara [5]. Figure 10 shows a comparison of simulations with varying amounts of spherical aberration and defocus and experimental images with the coated CD-R disk.

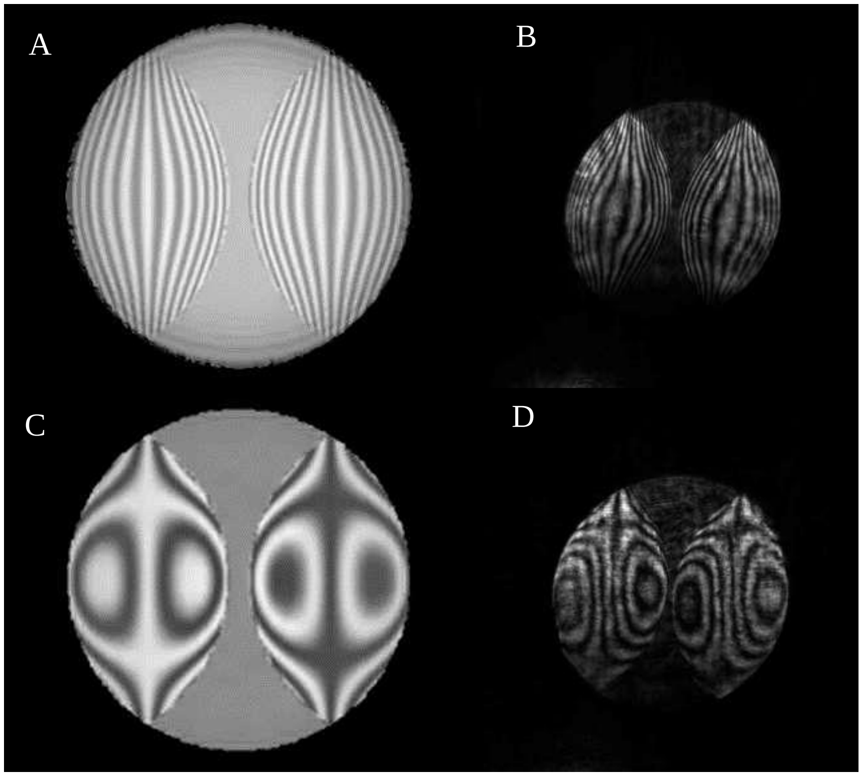


Figure 10. Comparison of simulation and experiment with a gold-coated CD-R disk. A) Simulated 6 waves of spherical aberration; B) Experimental result; C) Simulated 6 waves of spherical and -6 waves of defocus; D) Experimental result.

5. CONCLUSION

For a sample with a diffractive surface, such as optical storage medium, there is an additional diffractive effect that propagates through a system that is not present with incoherent objects. Simulations and experiments indicate that, while this additional effect can be detected by the wavefront sensor, system aberrations dominate over the phase error that originates from the diffractive grooves. Therefore, adaptive optics *can* be utilized to correct for aberrations and recover a high-quality focus spot in systems with diffractive samples.

ACKNOWLEDGMENTS

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